



ACTIVE FORCE GENERATION/ISOLATION SYSTEM EMPLOYING MAGNETO RHEOLOGICAL FLUID (MRF)

Technical Field

[0001] This invention relates to vibration isolators, and more particularly, to a new and useful isolation system for minimizing in-plane vibrations produced in a rotating system, and still more particularly, to an isolation system that employs a Magneto Rheological Fluid (MRF) as the working inertial mass of the system. The MRF isolation system minimizes system weight, aerodynamic drag, and complexity while concomitantly providing active control and adjustment during operation for optimal efficacy across a wide spectrum of operating speeds.

Background of the Invention

[0002] Vibration isolation and absorption is often desirable for nulling or canceling vibrations associated with a rotating system. Such vibrations, when left unattenuated or unabated, may lead to structural fatigue and premature failure of system components. Furthermore, inasmuch as such vibrations may be transmitted through adjacent support structure to, for example, an aircraft avionics bay or to areas occupied by passengers, other components and cabin area remote from the source of the vibration, may be subject to these same potentially damaging or disturbing vibrations (albeit perhaps lower in amplitude due to energy absorption by the interconnecting structure). Consequently, it is most desirable to isolate or absorb these vibrations at or near the source of the vibration in the rotating system.

[0003] One application which best exemplifies the need for and advantages derived from vibration isolation/absorption devices is the main torque driving hub of a helicopter rotor system. Typically, the main rotor of a helicopter, which comprises a central torque drive hub member for driving a plurality of lift producing rotor blades, is subject to a variety of aerodynamic and gyroscopic loads. For example, as each rotor blade advances or retreats relative to the freestream airflow, it experiences a sharp rise and fall of in-plane aerodynamic drag. Furthermore, as the tip of each rotor blade advances with each revolution of the rotor system, the relative velocity seen by the blade tip approaches supersonic Mach numbers. As such, large variations are caused to occur in the various coefficients which define blade performance (e.g.,

moment, lift and drag coefficients). Moreover, gyroscopic and Coriolis forces are generated causing the blades to “lead” or “lag” depending upon cyclic control inputs made to the rotor system. All of the above, generate substantial in-plane and out-of-plane vibrations, which, if not suppressed, isolated or otherwise abated, are transmitted to the cockpit and cabin, typically through the mounting feet of the helicopter main rotor gearbox.

[0004] Various vibration isolation systems have been devised to counteract/oppose and minimize these in-plane and out-of-plane vibrations. Mast-mounted vibration isolators suppress or isolate in-plane vibrations at a location proximal to the source of such in-plane vibrations whereas transmission, cabin or cockpit absorbers dampen or absorb out-of-plane vibrations at a location remotely disposed from the source. Inasmuch as the present invention relates to the isolation of in-plane vibrations, only devices designed to counteract/oppose such vibrations will be discussed herein.

[0005] Vincent et al. U.S. Pat. Nos. 4,145,936 and 4,225,287 disclose mast-mounted vibration isolators having a plurality of resilient arms (i.e., springs) extending in a spaced-apart spiral pattern between a hub attachment fitting and a ring-shaped inertial mass. Several pairs of spiral springs (i.e., four upper and four lower springs) are mounted to and equiangularly arranged with respect to both the hub attachment fitting and the inertial mass so as to produce substantially symmetric spring stiffness in an in-plane direction. The spring-mass system, i.e., spiral springs in combination with the ring-shaped mass, is tuned in the non-rotating system to a frequency equal to $N * \text{rotor RPM}$ (e.g., 4P for a four-bladed rotor) at normal operating speed, so that in the rotating system it will respond to both $N+1$ and $N-1$ frequency vibrations (i.e., 3P and 5P for a four-bladed rotor). N is the number of rotor blades.

[0006] While the spiral spring arrangement of the ‘936 and ‘287 patents produces a relatively small width dimension (i.e., the spiraling of the springs increases the effective spring rate), the height dimension of each vibration isolator is increased to react out-of-plane loads via the upper and lower pairs of spiral springs. This increased profile dimension increases the profile area, and consequently the profile drag produced by the isolator. Furthermore, the spiral springs must be manufactured to precise tolerances to obtain the relatively exact spring rates necessary for efficient operation. As such, manufacturing costs are increased. Furthermore, these vibration isolators are passive devices which are tuned to a predetermined in-plane frequency. That is, the

vibration isolators cannot be adjusted in-flight or during operation to isolate in-plane loads which may vary in frequency depending upon the specific operating regime.

[0007] U.S. Patent 3,540,809, 4,057,363 & 4,083,654 issued to inventors Kenigsberg and Paul et al., disclose yet another general configuration of isolator known as a “bifilar”. These mast-mounted vibration isolators comprise a hub attachment fitting connected to and driven by the helicopter rotorshaft, a plurality of radial arms projecting outwardly from the fitting and a mass coupled to the end of each arm via a rolling pin arrangement. That is, a pin rolls within a cycloidally-shaped bushing thereby permitting edgewise motion of each mass relative to its respective arm. The geometry of the pin arrangement in combination with the centrifugal forces acting on the mass (imposed by rotation of the bifilar) results in an edgewise anti-vibration force at a 4 per revolution frequency which is out-of-phase with the large 4 per revolution (or “4P” as it is commonly referred to as helicopter art) in-plane vibrations of the rotor hub for a 4 bladed helicopter. The frequency of 4P is the frequency as observed in a nonrotating reference system.

[0008] More specifically, pairs of opposed masses act in unison to produce forces which counteract forces active on the rotor hub. In Fig. 1, a schematic of a pair of bifilar masses are depicted to illustrate the physics of the device at an instant of time. Therein, the masses MI, MII are disposed at their extreme edgewise position within each of the respective cycloidal bushings BI, BII. The masses MI, MII produce maximum force vectors $F/2$, which produce a resultant vector F at the center, and coincident with the rotational axis, of the rotating system. Furthermore, the combined or resultant force vector F is equal and opposite to the maximum vibratory load vector P active on the rotor. It will also be appreciated that for the masses to produce the necessary shear forces to react the in-plane vibratory loads of the rotor system, counteracting bending moments are also produced. These force couples impose large edgewise bending loads in the radial arms, and consequently, the geometry thereof must produce the necessary stiffness (EI) at the root end of the arms. As such, these increased stiffness requirements effect larger, heavier bifilar arms.

[0009] While the bifilar system has proven effective and reliable, the weight of the system, nearly 210 lbs, is detrimental to the overall lifting capacity of the helicopter. For example, the weight of the bifilar system displaces a passenger and/or increases fuel consumption. To appreciate the significance of the increased weight, it has been estimated that

for each pound of additional weight, direct operating cost of the helicopter increases by approximately \$10,000. Furthermore, the pin mount for coupling each mass to its respective radial arm routinely and regularly wear, thus requiring frequent removal and replacement of the cyclical bushings. This increases the Direct Maintenance Costs (DMC) for operating the helicopter, which contributes, to the fiscal burdens of the bifilar system and the helicopter.

[00010] Therefore, a need exists for an isolation system to reduce vibrations in a rotating system that isolates a wide spectrum of vibratory loads; especially large amplitude loads, minimizes system weight, reduces aerodynamic drag, and reduces DMC.

Disclosure of the Invention

[00011] It is the object of the present invention to provide a Magneto Rheological Fluid (MRF) vibration isolation system that is controllable for varying the range of isolation frequencies.

[00012] It is another object of the present invention to provide such an MRF vibration isolation system that absorbs large amplitude vibrations while minimizing system weight.

[00013] It is still a further object of the invention to provide such an MRF isolation system that minimizes aerodynamic drag.

[00014] It is still another object of the present invention to provide such an MRF vibration isolation system that employs reliable, long-life components/elements for reducing DMC.

Brief Description of the Drawings

[00015] A more complete understanding of the present invention may be had by reference to the following detailed description when considered in conjunction with the accompanying drawings wherein:

[00016] Fig. 1 is a schematic of a prior art bifilar isolation device for illustrating certain physical characteristics thereof.

[00017] Fig. 2 is a side sectional view of a helicopter main rotor, including a main rotor shaft having an MRF isolation system according to the present invention mounted to the upper mast or shaft extension member of the rotor.

[00018] Figs. 3a – 3c depict schematic views of various operating conditions of the inventive isolation system.

[00019] Fig. 4 is a side sectional view of a vibration absorber.

[00020] Fig. 5 is a schematic view of an alternative isolation system with stationary electromagnets.

Best Modes for Carrying Out the Invention

[00021] —The vibration isolation system 10 of the present invention is described in the context of a helicopter rotor system, such as that employed in an Army BLACK HAWK helicopter produced by Sikorsky Aircraft Corporation. One skilled in the art, however, will appreciate that the present invention has utility in any rotating system that produces vibratory loads. The invention is especially useful in rotating systems that produce large vibratory loads that vary depending upon different operating regimes or variable operating speeds.

[00022] Referring to Figs. 2 and Fig 4, the MRF vibration ~~isolator~~ isolation system 10 according to the present invention is disposed in combination with a helicopter main rotor system 2 ~~comprising~~ including a main rotor shaft 4 which is driven about ~~its~~ a rotational axis 6 by a torque driving transmission 8. In the described embodiment, the main rotor system 2 ~~also comprises a propeller type~~ includes a rotor hub 12 having four radial arms, which mount to and drive each rotor blade 16. The vibration isolation system 10 is mounted to a flanged ~~end~~ segment 13 of the main rotor shaft 4 ~~by means of~~ through a hub attachment fitting 18. Vibratory forces active on the main rotor system 2 are generated by a variety of factors, although the dominant vibrations originate from aerodynamic and/or gyroscopic forces generated by each rotor blade 16. A four bladed rotor system produces 4P vibratory loads. In a single revolution, the magnitude of the load vector varies from a minimum to a maximum value four times. While a variety of factors influence the vibratory spectrum of a rotor system, such 4P vibrations are generally a result of each rotor blade experiencing maximum lift when advancing and minimum lift when retreating. This vibration frequency can be more generally depicted by the term NP where N is the number of blades and P is the ~~rotor~~ rotational speed of the rotor hub 12 of the helicopter main rotor system 2.

[00023] Referring to Figs. 2 through 5 the vibration isolation system 10 ~~comprises~~ includes a housing 20 containing a MRF 26, ~~a means 32~~ field generation system 28 for controlling the distribution of the MRF 26 within the housing 20, ~~a means 34~~ drive system 30 for driving an enclosed chamber 22 about the rotational axis of the rotor shaft 4, and a ~~power generation means~~ generator system 60 for ~~energizing~~ powering the ~~fluid distribution and drive means, 32 and 30 respectively~~ field generation system 28 and drive system 30. More specifically, the housing 20 defines ~~a substantially circular internal cavity or~~ the enclosed chamber 22 for

containing the MRF 26, which partially fills the chamber 22. The ~~means-32~~drive system 30 for distributing the MRF 26 within the chamber 22 includes: a field generation ~~means~~system 28 capable of producing an electromagnetic field within the chamber 22, a ~~means-32~~electric motor 34 for displacing the MRF 26 within chamber, and a control ~~means~~system 40. In the preferred embodiment, the field generation ~~means~~system 28 ~~comprises a plurality of electromagnets~~includes a multiple of electromagnets 32 disposed about the periphery of the chamber 22 including at least one electromagnet 36 disposed externally of the chamber 22 for effecting MRF flow in a direction opposing the rotational direction of the housing 20. ~~Further, the displacement means 32, in combination with the field generation means 28, causes~~The field generation system 28 and the drive system 30 provides a selective build- up or collection of MRF 26 in a desired location within the chamber 22 (Figures 3A-3C). The control ~~means~~system 40 selectively varies the flux of the electromagnetic field generated by the multiple of electromagnets 32 while additionally controlling the ~~displacement means 32~~drive system 30. More specifically, the multiple electromagnets 32 ~~which~~ produce the magnetic field within or about the chamber 22 ~~are responsive~~in response to flux field control-signals 48s issued by the control ~~means~~system 40. The flux field control-signals 48s are indicative of strength and phase of the electromagnetic flux field, which may be varied to establish and/or alter the azimuthally varying viscosity of the MRF 26. Further, drive control signals 44s are issued to the ~~displacement means 34~~drive system 30 for varying the speed and phase of the chamber 22 within the housing 20.

[00024] Before addressing the operation of the isolation system in yet greater detail, it is useful to describe the properties and characteristics of a magneto-rheological fluid. Magneto-Rheological Fluid (MRF) is a composition that changes state, i.e., from fluid to solid or solid to fluid, depending upon the magnitude of an electrical field, i.e., when the MRF is exposed an electromagnetic field. While the physical change is, in the most precise scientific terms, a change in viscosity of the MRF, the change may, more practically and descriptively, be viewed as a change in state i.e., from fluid to solid and visa versa. At the molecular level, upon exposure to an electric field, the molecules align in columns so as to develop compressive and bending strength/stiffness. When exposed to a high flux field, the MRF is highly viscous, develops high stiffness in compression and bending, and, consequently, cannot be readily deformed. As the

flux field decreases in strength, the MRF becomes less viscous, may flow and, therefore exhibits fluidic properties.

[00025] Returning to our discussion of the vibration isolation system 10, the field generation ~~means~~system 28, ~~distribution means~~ 32 drive system 30 and control ~~means~~system 40 enable the MRF 26 to change its state, shape, orientation or position within the chamber 22 through selectively energizing/de-energizing certain of the multiple of electromagnets 32 and physically distributing the MRF 26 therein. That is, by selectively changing the electromagnetic flux field and assisting/effecting the collection of MRF 26 in a particular location, the MRF 26 flow may be caused to move to desired positions within the chamber 22. The field generation ~~means~~system 28 is responsive to the ~~controller means~~control system 40 to selectively power one or more of the multiple of ~~electromagnet or~~ electromagnets 32 to the desired strength.

[00026] Figures 3A-3C and 4 show that a large flux field signal 48s to the field generation ~~means~~system 28 will result in ~~larger~~ a significant accumulation of MRF 26 and thus a larger ~~vibratory force~~ eccentric mass (Figure 3A). A zero signal will result in no accumulation thus the centrifugal forces will cause the MRF 26 to distribute uniformly on the chamber inner periphery producing zero vibratory force (Figure 3C). The field generation ~~means~~system 28 is ~~powered~~ selectively controlled by signals from the ~~controller~~ 44 control system 40. These flux field signals 48s pass through a slipring 48-54 to the multiple of electromagnets 32. To facilitate the desired movement of the MRF 26 within the chamber 22, the chamber 22 may have a variety of internal shapes including toroidal, annular or cylindrical. Further, the chamber 22 may be internally segmented or segregated to define a multiple of chambers capable of shuttling fluid to the appropriate position or minimizing the size of the electromagnets 32. A physical agitation ~~means~~system 35 may be provided to speed the movement of the MRF 26 to allow swift transitions from one force output magnitude to another. Alternatively, a stationary magnet 3635' may ~~be used to achieve~~ provide agitation. Stationary magnet 35' is non-rotating. Being non-rotating but proximate to chamber 22 that encloses the MRF 26, stationary magnet 35' tends to mix the MRF 26 as the housing 22 rotates relative thereto.

[00027] ~~The isolation system 10 also includes a means 30 for driving~~ The electric motor 34 independently drives the chamber 22 and MRF 26 about the ~~rotational axis of rotation~~ 6 of the main rotor shaft 4. In the preferred embodiment, the drive ~~means~~system 30 preferably

~~comprises~~includes an electric motor 34 for driving the chamber 22. The drive ~~means~~system 30 is also responsive to control signals issued by the control ~~means~~system 40. More specifically, the control ~~means~~system 40 ~~comprises~~includes: a speed sensor 46 for obtaining input speed signals 46s indicative of the rotational speed 1P of the main rotor shaft 4, and a ~~controller~~signal amplifier ~~means~~ 44, responsive to the input speed signals 46s, for issuing control signals 44s to the drive ~~means~~system 30. The input speed signal 46s and the electrical power signals 60s are transmitted from a stationary system such as a fuselage to the rotating counterparts 46s and 50s/60s respectively by ~~means of~~ a slip ring 54

[00028] In operation, and referring to Figs. 3a – 3c, the MRF 26 is solidified or frozen in a particular position and, as such, functions as the working or inertial mass of the system 10. More specifically, the MRF 26 ~~or system mass~~ is (i) disposed at a predetermined distance R from the main rotor shaft axis of rotation 6, (ii) driven in the same or opposing rotational direction as the main rotor shaft axis of rotation 6 and (iii) driven at a rotational speed greater than the rotational speed 1P of the rotor shaft. While the speed sensor 46 may be a dedicated unit for sensing rotor speed, the same information may be obtained from a transmission driven alternator or generator 60, ~~shown in~~ (Figure 4), which turns at a predefined speed relative to the rotor speed. The power source 60 is preferably a 15 kVa generator which provides a 115 volt, 400 Hz 3 phase potential drives the electric motor 34 and simultaneously provides the reference signal. The generator is mechanically driven by torque driving transmission 8. As a result, the rotational speed of the generator is a fixed multiple of the speed of the driving gear in the gearbox and of the main rotor Np frequency. The electrical phase of the generator voltage is a fixed multiple of the generator rotational speed. Thus, the electrical voltage phase signal is a reflection of the Np frequency. As the rotor speed and Np frequency vary while in flight, the electrical voltage phase signal also varies and is perfectly slaved to i.e. a fixed multiple of the rotor speed. This fact makes the voltage signal a good reference signal that will exactly track rotor speed. Hence, the ~~controller 44~~control system 40 may use phase information from such devices to issue the appropriate control signals to the drive ~~means~~system 30 and to the field generation ~~means~~system 28.

[00029] While the ~~MRF~~vibration isolation system 10 may employ a ~~simple controller~~ 44-control system 40 having a predefined schedule or model of the vibrations, e.g., at prescribed

rotor speeds, the preferred embodiment also employs a vibration sensing device or system. As such, the control ~~means-system 40 further comprises~~ includes one or more vibration feedback sensors 51 for issuing vibration signals 51s indicative of the vibrations (e.g., amplitude, frequency and phase) in the helicopter, e.g., fuselage, cabin or cockpit. The control ~~means system 40~~, therefore, samples vibration levels at predefined intervals or rates to identify a trend - positive (lower vibration levels) or negative (larger vibration levels). Accordingly, as vibration levels change, the ~~controller-44~~ control system 40 issues modified control signals 44s and 48s to the drive ~~means-system 30~~ and the field generation ~~means-system 28~~ until ~~an optimum-a~~ combination of rotational speed and angular position of the MRF 26 center of gravity are achieved to minimize vibratory loads in the main rotor system 2.

[00030] The vibration isolation system 10 may be powered by any of a variety of known methods, especially methods which may require transmission from a stationary to a rotating reference system. In the described embodiment, the power source 60 for the drive ~~system 30, and control means, 30 and 40, respectively,~~ the control system 40, and the field generation system 28 is ~~at~~ a 15 kVa generator 60 which provides a 115 volt, 400 Hz 3 phase potential. Power is transferred from the stationary system to the rotating system via a ~~conventional cylindrical~~ the slip ring 54. Negligible additional weight is required inasmuch as the slip ring 54 is pre-existing ~~and used for powering~~ for other systems e.g., rotor blade de-ice system. Alternatively this slip ring 54 may also be used to communicate the control signals 44s, 48s, 51s to the drive ~~means~~ system 30 and the field generation ~~means~~ system 28 if the ~~controller-44~~ control system 40 is positioned in the non-rotating system.

[00031] In operation, the MRF ~~or working mass~~ 26 is driven at a rotational speed greater than the rotational speed of the ~~rotating system-main rotor system 2~~ and appropriately positioned to yield a load vector ~~P10~~ P₁₀ ~~in Fig 3(Figure 3A)~~ which is equal and opposite to the vibration load vector P2 produced by the ~~rotor system-2~~. This counteracting load vector ~~P10~~ P₁₀ can be viewed as a vector which attempts to cancel or null the displacement of the rotor shaft 4. Inasmuch as the drive ~~means-system 30~~ is mounted directly to the rotating shaft 4 of the main rotor system 2, the drive ~~means-system 30~~ need only drive the chamber 22 at three additional revolutions per cycle (for each revolution of the rotor system) in the direction of rotation of the main rotor system 2 to achieve the desired 4P operating frequency for a 4 bladed rotor. That is,

since the ~~working mass~~ MRF 26 is, in ~~a~~ the rotating reference system, driven at one revolution per cycle by the main rotor system 2 itself, the drive ~~means-system~~ 30 need only augment the rotational speed 1P of the main rotor system 2 by 3P, provided that the augmentation is in the same rotational direction, to achieve the necessary 4P (computed by $1P+3P = 4P$) frequency ~~in~~ relative to the stationary reference system. Alternatively, the augmented rotation can be opposite to the rotor speed 1P. For example the drive ~~means-system~~ 30 can augment the rotational speed 1P by rotating the chamber 22 at 5P in the opposite direction to achieve the necessary 4P (computed by $1P-5P = -4P$) frequency in the stationary reference system. For any number of rotor blades, the absolute frequency to suppress is NP where N is the number of rotor blades. The augmentation speed of the chamber 22 produced by the drive ~~means-system~~ 30 is then $(N-1)P$ in the direction of the rotor speed or $(N+1)P$ in the opposite direction.

[00032] The embodiment ~~shown~~ of Figure 5 has the advantage of not requiring an electrical slip ring 4854 to position the eccentric mass that provides the anti-vibration force. In this embodiment, the electro-magnets 32 do not rotate ~~and~~ with the chamber 22 (Figure 4), but are stationary. The electric power ~~wires-28~~ coils 33 are also stationary. The ~~completely sealed enclosure~~ housing 20 forms an enclosed ~~volume-chamber~~ 22. The MRF 26, in this example, rotates about the ~~center-axis~~ of rotation 6 ~~by means of~~ the shaft 4. In this case the shaft 4 and the ~~enclosure-housing~~ 20 rotate together and in the counterclockwise direction at a frequency of 3P, for a 4 bladed rotor, relative to the main rotor system 2. The rotation of the shaft 4 about the ~~center-axis~~ of rotation 6 at a frequency of 3P ~~can be~~ is achieved with an electric motor or other means. The electric power to the ~~wire-power~~ coils 28-33 is switched to the successive electromagnets ~~2832~~ in the counterclockwise direction such that the magnet field rotates at the same rotational speed as the shaft 64 and ~~volume-chamber~~ 22. As a result, the maximum magnetic field rotates at the same rotational speed as the ~~volume-chamber~~ 22 and is thus stationary relative to the ~~enclosure-housing~~ 20. As a consequence, the MRF 26 accumulates in the ~~enclosure-housing 20 and volume-22~~ at ~~the~~ a point of the maximum magnet field. In this manner, the bulk of the MRF 26 forms an eccentric mass according to the commanded phase of the magnetic field position. The resulting eccentric mass causes an eccentric centrifugal force that can be adjusted to suppress the unwanted ambient force.

[00033] ~~Lessening or increasing the amount electrical current applied to the wire 28 can vary power coils 33 varies~~ the amount of MRF 26 that accumulates at a chosen angular location in the ~~volume~~housing 22. In an extreme case, the current can be zero or very low. This condition will cause the MRF 26 to be distributed uniformly around the periphery of the ~~volume~~chamber 22 (Figure 3C). As the amount of current sequentially applied to the ~~wires 28~~power coils 33 of the electromagnets 3232' is increased, the amount of MRF 26 that accumulates at the chosen azimuth phase in the ~~volume~~housing 22 will increase, thus causing a correspondingly large eccentric force to suppress an unwanted ambient force.

[00034] A stationary permanent magnet 3635' can be placed near the ~~enclosure~~housing 20 for a beneficial effect of causing the MRF 26 in the ~~volume~~chamber 22 to mix more readily. This will have the effect of speeding the change in position of MRF 26 to a desirable location when the location desired is changed to reduce a changing magnitude or phase of unwanted ambient force.

[00035] ~~The ability to independently~~Independently ~~vary~~varying the location and magnitude of the MRF 26 within the housing 20 is especially valuable in applications wherein the magnitude of the vibratory load active in/on the rotating system varies as a function of operating regime or operating speed. In a rotorcraft, for example, it is common to require the highest levels of vibration isolation in high speed forward flight i.e., where the rotor blades are experiencing the largest differential in aerodynamic loading from advancing to retreating sides of the rotor system. Consequently, it may be expected that the vibration isolation system 10 produce a maximum load vector ~~P10_{max}~~ P_{10max} ~~as shown in~~ (Figure 3a). In ~~yet~~another example, it is anticipated that the lowest levels of vibration isolation would be experienced in a loiter or hovering operating mode, where the rotor blades are exposed to the same aerodynamic and gyroscopic affects. Consequently, it may be expected that the vibration isolation system 10 produce no or a minimum load vector, P10_{min} ~~in~~ (Figure 3c).

[00036] In summary, the ~~MRF~~vibration isolation system 10 is capable of nulling or canceling vibrations across a wide frequency spectrum. That is, the vibration isolation system 10 is capable of varying its operating frequency irrespective of changes in operating regime or operating speed. Furthermore, the vibration isolation system 10 employs few moving parts, thus increasing reliability while reducing Direct Maintenance Costs. While the prior art bifilar

requires frequent repair or replacement of the cycloidal bushings, the MRF 26 does not induce wear. Moreover, the vibration isolation system 10 employs fixed components such as electromagnets which are highly reliable and require negligible if any maintenance. Finally, the vibration isolation system employs a low profile circular housing 20. As such, the vibration isolation system 10 of the present invention reduces aerodynamic drag when compared to prior art spiral spring isolators (discussed in the background of the invention).

[00037] Although the invention has been shown and described herein with respect to a certain detailed embodiment of a mast-mounted helicopter isolator, it will be understood by those skilled in the art that a variety of modifications and variations are possible in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the present invention may be practiced otherwise than as specifically described hereinabove.